TD-04-012
March 31, 2004

AN UPGRADED SC TRANSFORMER TO TEST RUTHERFORD CABLES AT SELF-FIELD

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Abstract:

The secondary winding design of the original transformer [1], which was used to study Nb_3Sn cable splicing techniques, was modified to accommodate a cable sample of about three pitch lengths as opposed to about half a pitch in the previous design. The basic objective of this new transformer was to measure the quench current of SC cables at self-field under various cooling conditions. Possible additional objectives by means of a faster DAQ system [2] included quench localization and spike detection. To increase the maximum capability of the secondary current, a primary circuit with larger number of turns was designed and fabricated. This improved the maximum secondary current from 22.5 kA to nearly 28 kA.

1. INTRODUCTION

As the hypothesis of instability phenomena in Nb_3Sn became more and more plausible, the decision was made of modifying the secondary winding of the existing SC transformer [1] to test cables at self-field. As instability is a phenomenon that shows itself at low fields, cable tests at self-field using the existing SSTF and strand power supply appeared to be the most efficient way to a fast turn-around and reliable data. In addition, since short sample limits of cos-theta models with typical strand Jc's of 2000 A/mm^2 are close to 25 kA, and those of the small racetracks about 28 kA, the primary winding was redesigned to accommodate 112 turns as opposed to 64 of the previous design. To extend its operational life, the primary was also impregnated. This note describes the new transformer design, sample preparation, instrumentation and mounting, test procedure and performance. The fast DAQ system that was implemented is illustrated in detail elsewhere [2].

2. TRANSFORMER DESIGN MODIFICATIONS

The original transformer is shown in Fig. 1. The primary multi-turn coil is placed inside the secondary single-turn winding. The 64 primary turns of the transformer were wound on a G-10 core using 0.8-mm NbTi strand (SSC inner layer strand) coated with 50-μm polyimide insulation. The secondary winding consisted of two U-shaped parts: a stabrite NbTi cable section of 27 x 1mm strands placed close to the primary coil for better magnetic coupling, and a pre-shaped and reacted removable section as the sample to be tested. It can be seen that the unspliced length of the sample was only about half a pitch length. After testing, this section could be removed and new samples could be inserted without disassembling the transformer. The calculated inductance of the primary winding $L1$, inductance of the secondary winding $L2$, and mutual inductance M, were $L1$ = 0.6 mH, $L2$ = 0.23 μH, and M = 7.3 μH respectively.

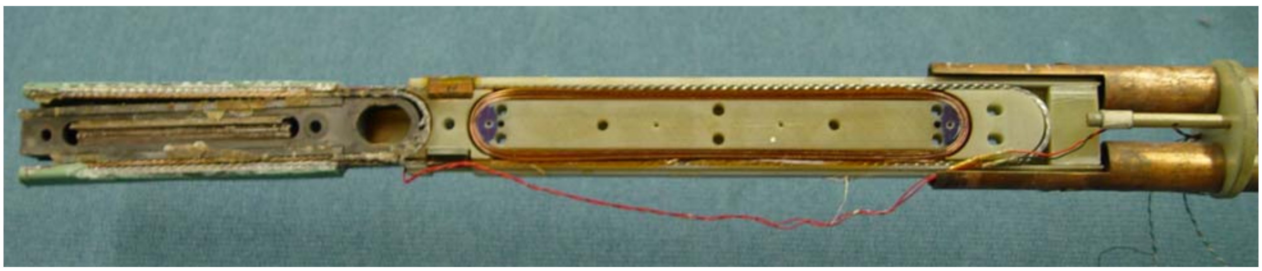

Fig. 1. The original superconducting current transformer.

The new shape of the transformer secondary circuit is shown in Fig. 2. Only the double-bent stabrite NbTi cable section of 27 x 1mm strands is shown in the picture. On the left bend is placed a two-layer heater, whose parameters are: No. turns = 201, Total resistance = 100 Ohm, Length = 22.8 ft. Before the right bend is a 4-winding Rogowski coil. The sample to be tested was placed in the straight groove of the G-10 structure and spliced to the NbTi cable ends. However, during commissioning, the more convenient solution of cutting the G-10 bottom wall in Figure below and using it as a pusher on the cable sample was implemented. After testing, the sample can be removed and a new sample inserted without risk of damage to the primary coil or to the cable.

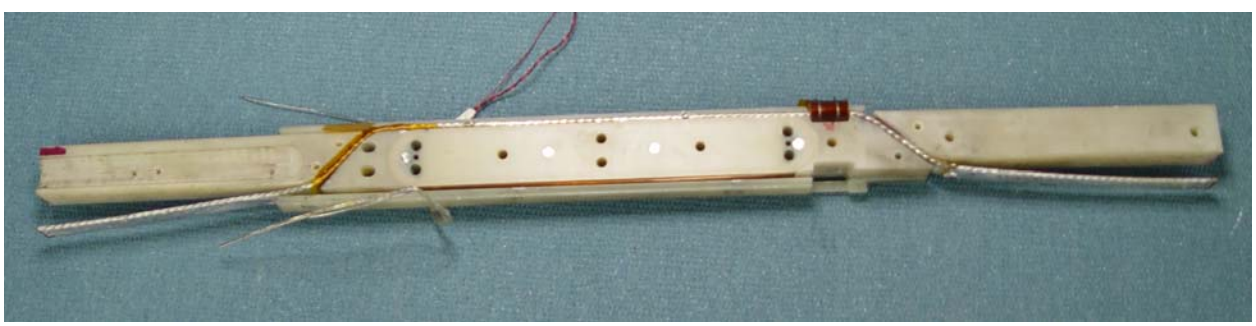

Fig. 2. G-10 structure with groove showing the new shape of the secondary winding. Only the double-bent stabrite NbTi cable section is shown in the groove.

Fig. 3 shows the winding process of the new primary coil, made out of 112 turns over 6 layers. The same SSC coated strand was used on a smaller G-10 island, but fiberglass cloth was also added as an insulation between layers. After winding, the primary was enclosed around the sides between two G-10 end parts and aluminum strips, and covered at the top and the bottom with G-10 strips with appropriate holes for the vacuum outlet and epoxy inlet, as shown in Fig. 4. After RTV sealing, vacuum impregnation was performed using CTD epoxy. The impregnated coil is shown in Fig. 5.

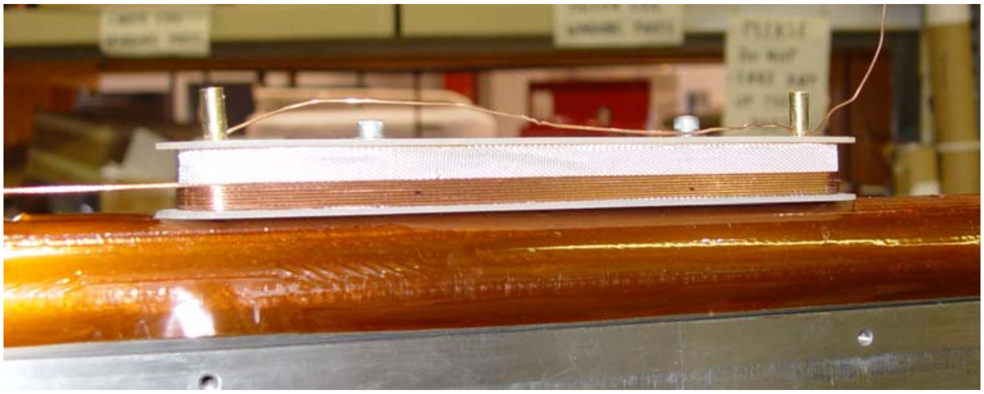

Fig. 3. Winding process of new primary coil. Fiberglass cloth is visible underneath turns.

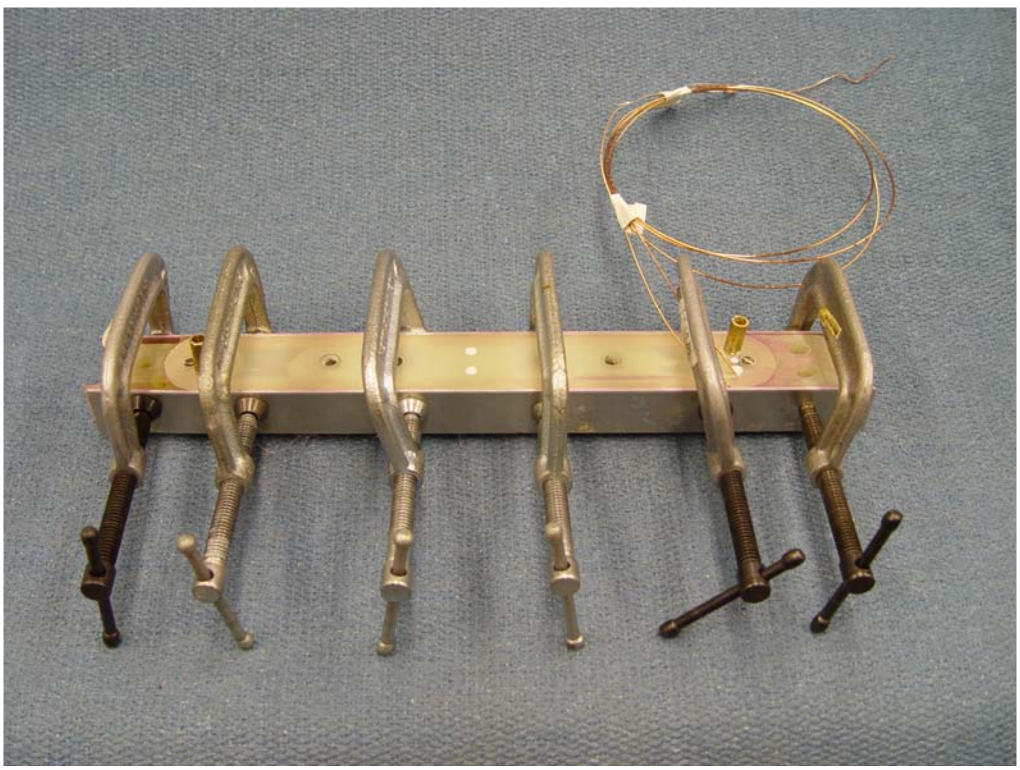

Fig. 4. Primary coil clamped before RTV sealing for impregnation.

Fig. 5. Primary coil after CTD vacuum impregnation.

A solid modeling of the new primary and secondary windings together is shown in Fig. 6.

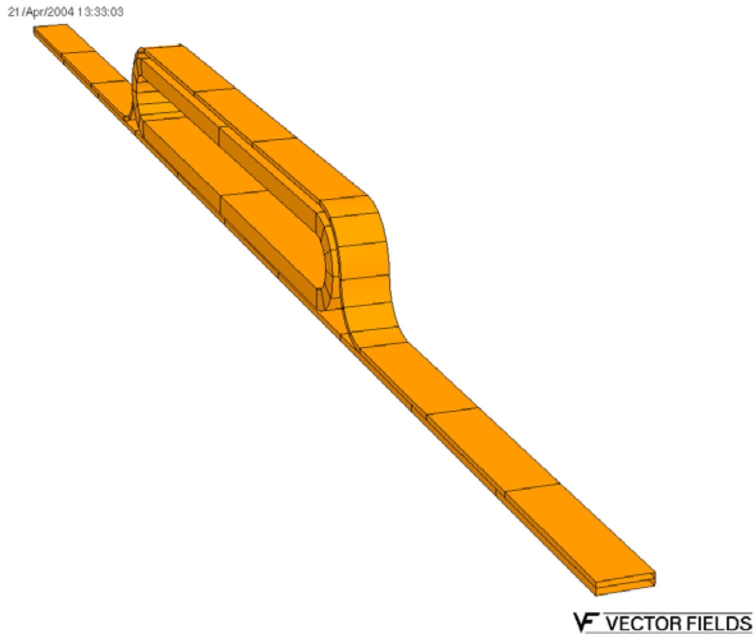

Fig. 6. Solid modeling of new primary and secondary windings together.

3. SAMPLE PREPARATION, INSTRUMENTATION AND MOUNTING

3.1 Sample Preparation

The Nb_3Sn cable samples are heat treated in argon in the large oven in IB3 using SS sample holders that have a groove deep enough to accommodate several cables. Samples are typically tested with ceramic insulation and binder, or epoxy impregnated. The following convenient CTD impregnation procedure was devised.

The cable sample is sandwiched over its insulated length between two G-10 strips 1 mm thick. If the sample has to be instrumented with a cernox, a hole is made in the top G-10 strip to accommodate the sensor as in Fig. 7. The cernox is placed on top of a 1.5 mil kapton sheet, and secured in place by means of GE 7031 varnish. The hole is filled with 2850 FT stycast before applying the CTD epoxy and wrapping the cable assembly with shrink tape and heating it with hot air to shrink the tape around the assembly as in Fig. 8.

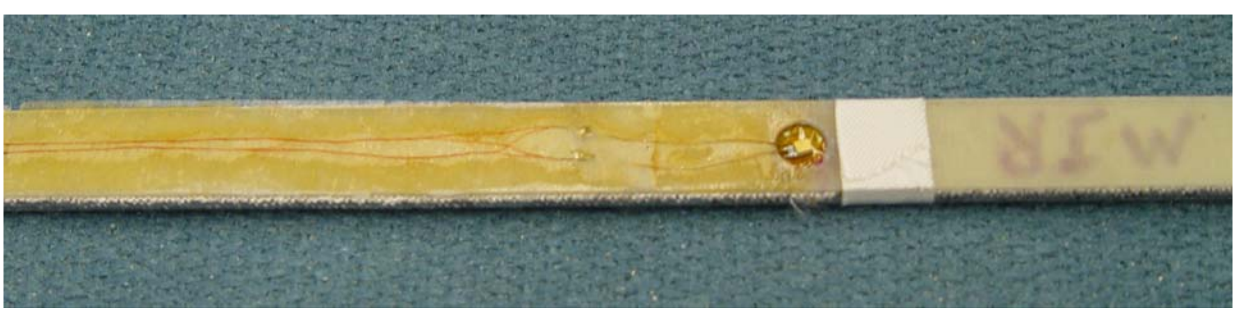

Fig. 7. The cernox is placed on top of a 1.5 mil kapton sheet. The cernox is secured in place with GE 7031 varnish. The cable sample is sandwiched over its insulated length between two G-10 strips 1 mm thick.

Then such assembly is placed in the same holder used for reaction and brushed again with CTD epoxy. The sample holder is closed and placed in the large oven (in air) for curing. Figs. 9 and 10 show an impregnated cable sample after the above procedure.

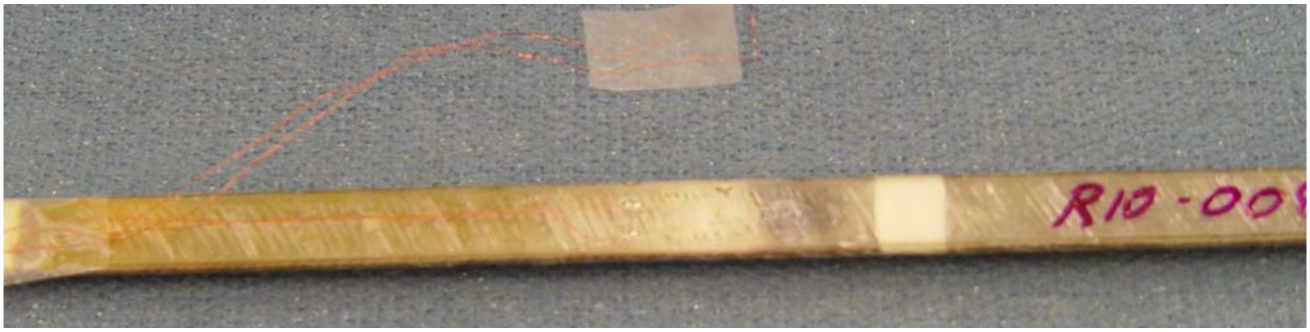

Fig. 8. After wrapping with shrink wrap, the cable is heated with hot air to shrink the tape around the assembly before being epoxy impregnated.

Fig. 9. Impregnated cable sample.

Fig. 10. Close-up of the narrow edge of an impregnated cable.

3.2 Sample Instrumentation

In addition to a heater to quench the current in the secondary before each primary new excitation step, and to a Rogowski coil to measure the secondary current, the transformer secondary winding is equipped with six pairs of voltage taps to monitor quench location and propagation. The six voltage signals, the integrated Rogowski signal and the primary current from the analogical output of the power supply are acquired with a NI DAQ card at 25 kHz rate [2]. The primary current and the secondary current from the integrated Rogowski are obtained also using the standard LabView DAQ code at about 0.8 Hz rate. However, such reading is not as accurate (i.e. real time) as that of the fast DAQ card. Voltage taps cover the whole length of the secondary loop. A typical setup is shown in Fig. 11. Three voltage pairs are placed on the straight section at equal distances, one across the straight section on the NbTi cable, one around one splice, and one at the ends of the bent NbTi cable.

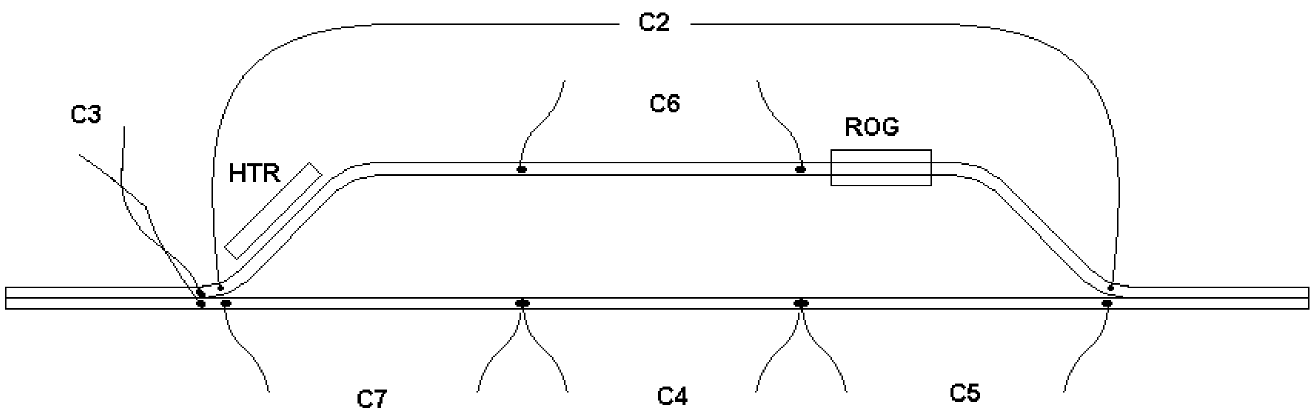

Fig. 11. Typical instrumentation setup during transformer test.

3.3 Sample Mounting

Before splicing the cable sample to the double-bent stabrite NbTi cable, a SS bar is placed on top of the splice being soldered. Clamps are used to control pressure during soldering of the top splice first and of the bottom splice next. In Fig. 12 the procedure is shown for the bottom splice. A 3 to 4 mm thick G-10 pusher is placed against the sample, and the bottom splice region is enclosed on three sides between G-10 strips (see Fig. 13), before being secured with SS wire. The SS bar used in the splicing procedure is placed on the top splice (see Fig. 14), which is then secured with two G-10 rings that are slid around it. Setscrews are used to apply pressure. SS wire is also used below the top splice. Adhesive fiberglass tape is used to cover the SS wire before wrapping the whole assembly with shrink tape (see Fig. 15), which is heated with hot air to shrink the tape around the assembly.

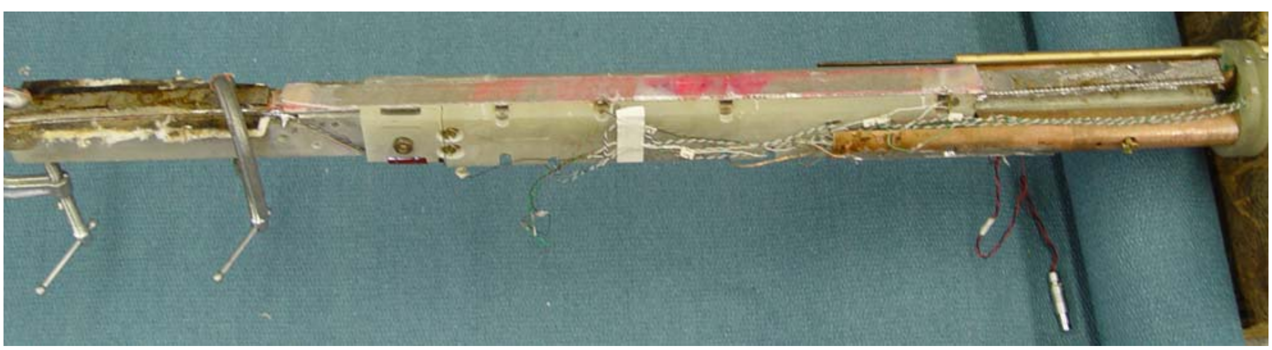

Fig. 12. Clamping pressure is increased appropriately during soldering of the top and bottom splices. The SS bar is visible on the bottom splice.

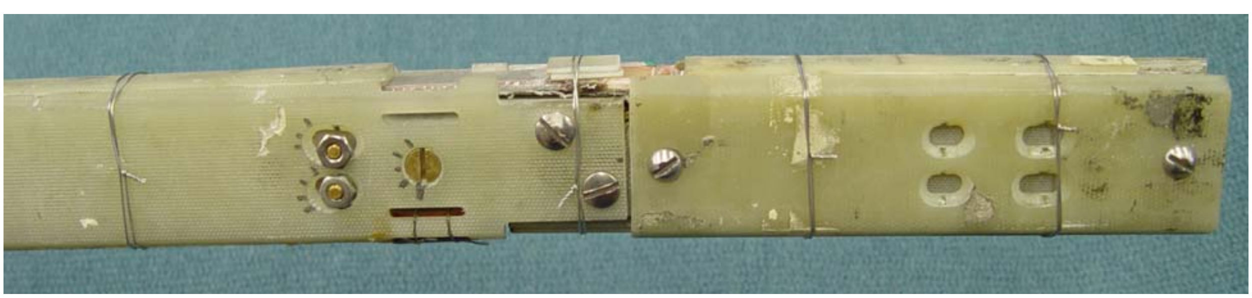

Fig. 13. The bottom splice is enclosed on three sides between G-10 strips before being secured with SS wire.

Fig. 14. The SS bar used in the splicing procedure is placed on the top splice, which is then secured with two G-10 rings that are slid around it. Setscrews are used to apply pressure.

Fig. 15. Adhesive fiberglass tape is used to cover the SS wire before wrapping the whole assembly with shrink tape.

4. TEST PROCEDURE AND PERFORMANCE

4.1 Test Procedure

Typical excitation diagrams are shown in Figs. 16 and 17 for the original transformer and for the upgraded one respectively. Both diagrams show the case of a cable sample reaching maximum current without quenching. As explained in [1], the main idea behind this test procedure is to reduce the magnetic field in the primary by ramping it in steps and quenching the secondary with the heater before starting a new ramping step in the primary. When the maximum current is attained in the primary and the secondary current is brought to zero, the primary coil is ramped down at various ramp rates. In the case of a cable sample that does not quench up to maximum secondary currents, the higher the ramp rate, the larger the current obtained in the secondary, as the time for the secondary current to decay is shorter. Thanks to the lower number of turns, in the original transformer a maximum primary current of about 870 A could be obtained in a series of ramp-hold steps. However, since for the same reason the transformer ratio was lower, the maximum secondary current was only about 22.5 kA, as seen in Fig. 16. In the upgraded transformer, a maximum primary current of about 750 A can be reached, leading to maximum secondary currents up to 27.5 kA if adequately high primary ramp rates are used. The plot in Fig. 17 illustrates the primary and secondary currents diagram as obtained from the standard LabView DAQ code for a test performed on an impregnated cable made of 28 x 1 mm PIT strands. In this case, the maximum current in the primary was 750 A, and the ramp rate used to bring the primary to zero was 80 A/s. A maximum secondary current of 25,687 A as obtained with the 0.8 Hz standard system was more accurately measured with the fast DAQ system as 26,243 A.

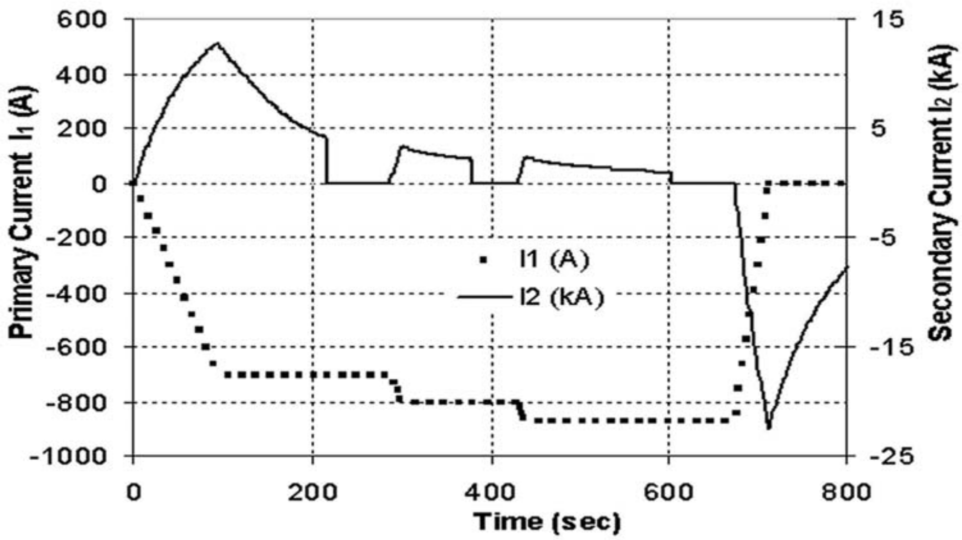

Fig. 16. Typical excitation diagram with original transformer in the case of a cable sample reaching maximum current without quenching.

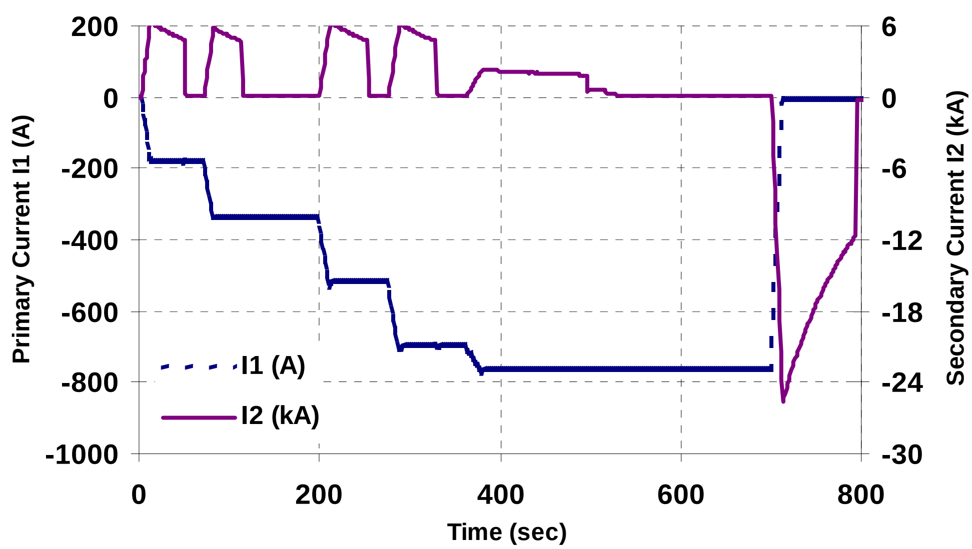

Fig. 17. Typical excitation diagram with new transformer obtained for an impregnated cable sample made of 28 x 1 mm PIT strands that reached maximum current without quenching. The maximum secondary current as measured with the fast DAQ system was 26,243 A.

4.2 Performance

To evaluate the maximum current capability of the stabrite NbTi cable of the secondary winding, a number of stabrite coated NbTi strands were extracted from such cable and tested. Results for the whole cable are the squares shown in Fig. 19. To calculate the transfer function of the secondary winding, which is B2/I2 = 0.0588 T/kA independently on the primary current, an Opera model was made. The field distribution obtained in the transformer due to 1 kA in the secondary winding is shown in Fig. 18. The intersection of the secondary load line with a linear approximation of the NbTi cable critical surface in Fig. 19 occurs at about 32 kA.

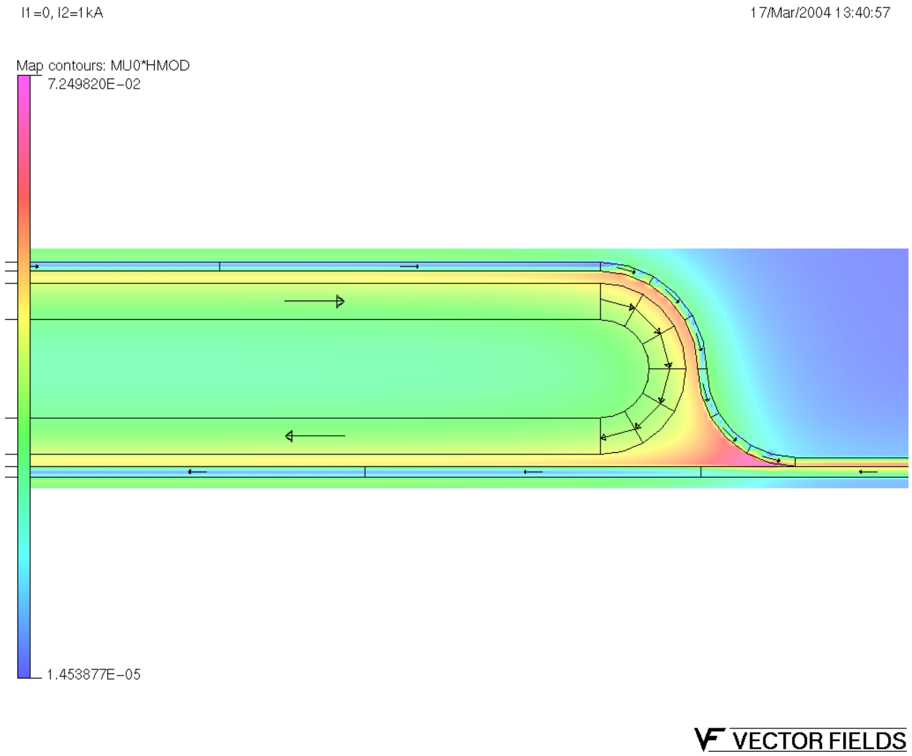

Fig. 18. Field distribution in the transformer due to 1 kA in the secondary winding.

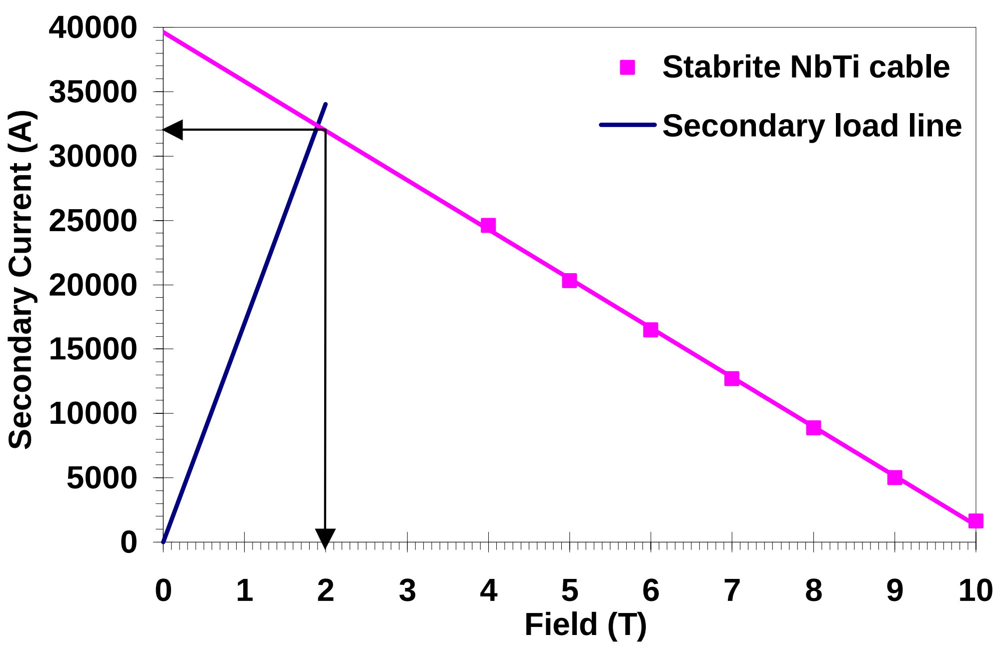

Fig. 19. Maximum current capability of the secondary winding as the intersection of the secondary load line with a linear approximation of the critical surface of the NbTi cable.

To evaluate the maximum current capability of the strand in the primary winding, a number of SSC strands were tested. Results are the squares shown in Fig. 21. The transfer function that were used for the primary winding, which are B1/N1/I1=0.0425 T/kA for the original transformer and B1/N1/I1=0.0497 T/kA for the new transformer, are those on the strand surface when the secondary current is zero. The field distributions were obtained with an Opera model with 1 kA in the primary winding, as shown in Fig. 20 for the new transformer. The intersection of the primary load line with the SSC strand critical surface in Fig. 21 occurs at about 750 A, consistently with the maximum currents obtained in the new primary.

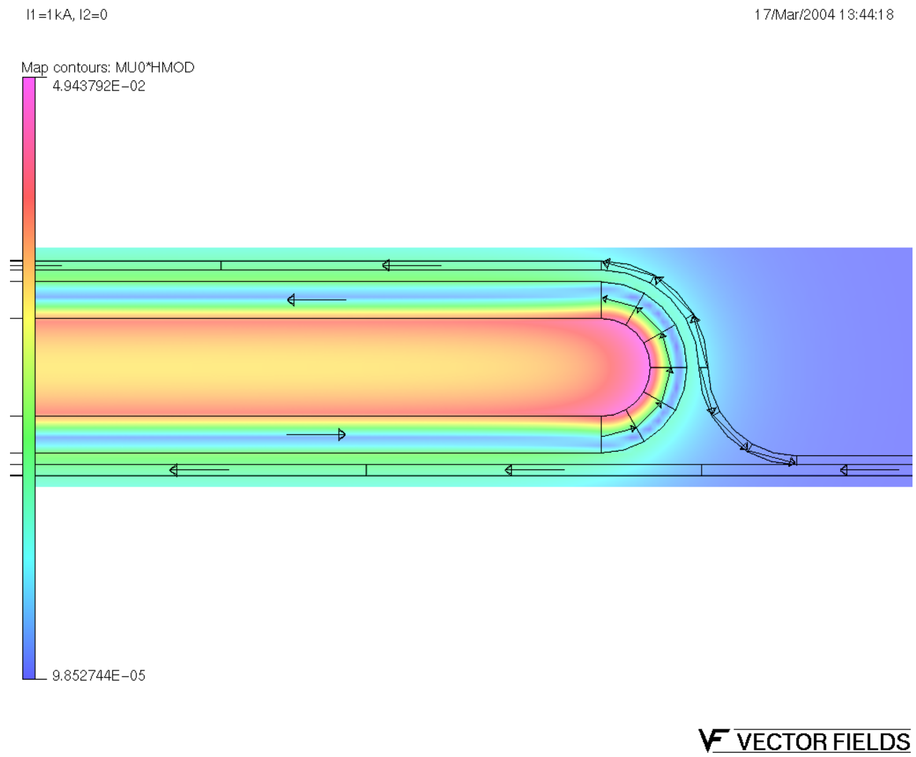

Fig. 20. Field distribution in the transformer due to 1 kA in the primary winding.

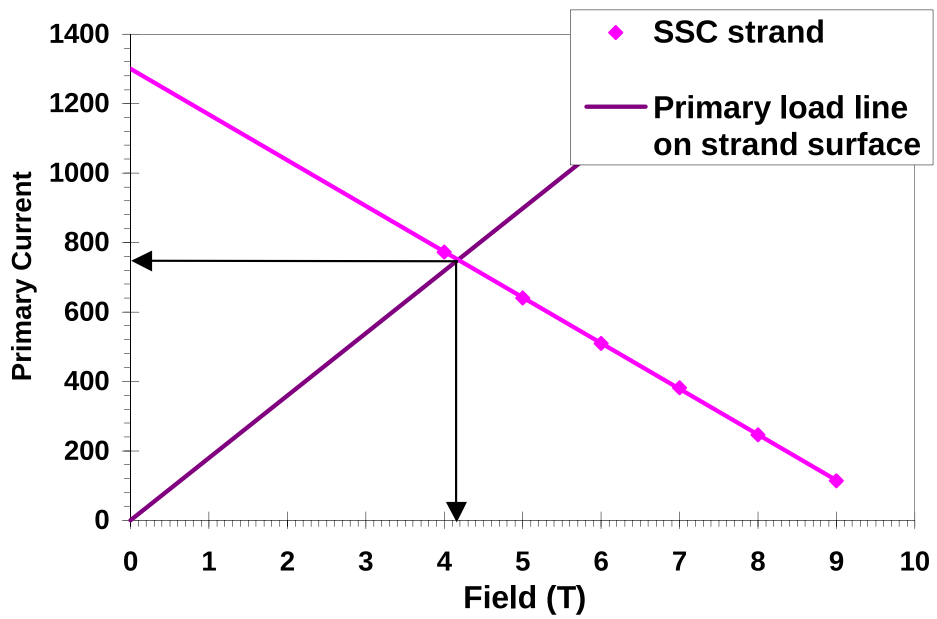

Fig. 21. Maximum current capability of the primary winding as the intersection of the primary load line with the critical surface of the SSC strand.

The quench history of the first test run performed at self-field on a Nb_3Sn cable with the new transformer secondary winding is shown by the blue lozenges in Fig. 22 for an impregnated cable made of 28 x 1 mm MJR strands and heat treated using the OST nominal cycle (i.e. RRR ~ 10). Two identical cables were simultaneously measured at various magnetic fields at the cable test facility at BNL [3]. The quench histories obtained in the FNAL and BNL test runs are shown in Fig. 22. The self-field during the FNAL test was about 1 T.

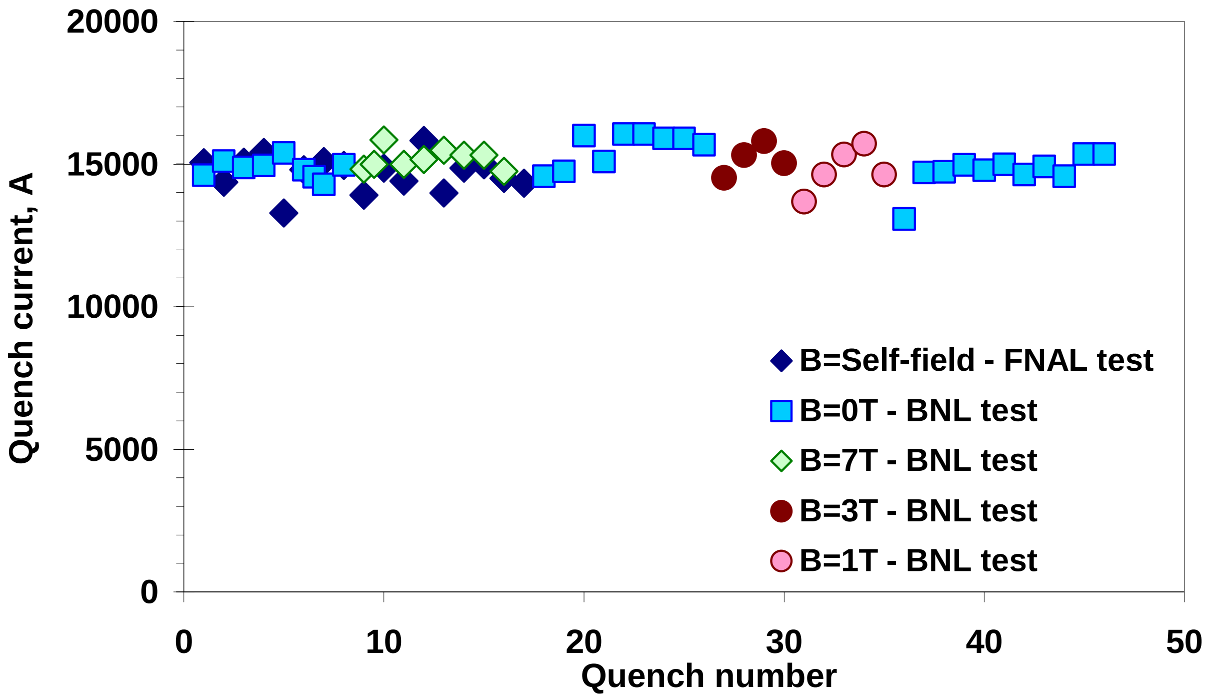

Fig. 22. Quench history results for an impregnated cable made of 28 x 1 mm MJR strands, heat treated using the OST nominal cycle, compared with cable test results performed at various fields on an identical cable at BNL.

5. CONCLUSIONS

A SC transformer with a different secondary design and upgraded primary winding with larger number of turns was built and commissioned. The performance of this transformer is consistent with the predictions. The maximum current in the secondary circuit is as large as 27.5 kA. The transformer is being extensively used to test impregnated and non-impregnated cables at self-field with a fast turn-around. The flexibility of the transformer architecture enables investigation of the various effects that have been tied to cable instability, such as deff, matrix resistivity, RRR and cooling. Systematic Nb_3Sn cable test results will be shown in the next technical note [4].

REFERENCES

[1] N. Andreev et al., *"Superconducting Current Transformer for Testing Nb_3Sn Cable Splicing Technique"*, 2002 Applied Superconductivity Conference, IEEE Transactions on Applied Superconductivity, V. 13, No. 2, June 2003, p. 1274.

[2] D. Turrioni, *"A Fast DAQ Solution for Transformer Tests at the SSTF"*, FNAL TD-04-011.

[3] G. Ambrosio et al., *"Test of Cables made of 1 mm OST-MJR Strand at BNL"*, FNAL TD-04-008.

[4] E. Barzi, D. Turrioni, *"Results of Nb_3Sn Cable Tests at Self-field using the Upgraded SC Transformer"*, FNAL TD-04-013.